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(54) Title: HEPATOBILIARY NMR CONTRAST AGENTS

(57) Abstract

A method of decreasing the NMR relaxation times (T_1 or T_2) of water protons in contact with a biological tissue, the method involving administering to a human patient an NMR contrast agent comprising a paramagnetic ion complexed with a chelating substance, the contrast agent being characterized in that it is capable of binding non-covalently and non-immunologically to a component of the tissue, and as a result of such binding is capable of enhancing relaxivity of the water protons by a factor of at least 2, compared to the relaxivity induced by the paramagnetic substance alone free in solution, and subjecting the patient to NMR imaging.

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HEPATOBILIARY NMR CONTRAST AGENTS

Background of the Invention

This invention relates to diagnostic NMR imaging.

NMR imaging has been used in medical diagnosis for a number of years. The use of contrast agents to enhance its diagnostic utility has only recently appeared. For example, Gries et al. German Patent DE 3,129,906 describes NMR contrast agents which consist of a paramagnetic ion complexed with a chelating agent and a base or acid, e.g., the di-N-methylglucosamine salt of manganese chelated with EDTA.

Summary of the Invention

The present invention provides an *in vivo* method of decreasing the NMR relaxation times of water protons in contact with a biological tissue. The method involves administering to a human patient an NMR contrast agent containing a paramagnetic metal ion complexed with a chelating substance, the contrast agent being characterized in that it is capable of binding non-covalently and non-immunologically to a component of the tissue, and as a result of such binding is capable of enhancing the relaxivity (i.e., decreasing the NMR relaxation times T_1 or T_2) of the water protons by a factor of at least 2, compared to the relaxivity induced in such water protons by the paramagnetic substance alone free in solution; and subjecting the patient to NMR imaging.

Preferably, the contrast agent has a specific affinity for the biological tissue in which binding occurs. (As used herein, "specific affinity" means capable of being taken up by, retained by, or bound to a particular tissue or tissue component to a substantially greater degree than other tissue or tissue components;

agents which have this property are said to be "targeted" to the "target" tissue or component.)

The components to which the agents of the invention bind are generally particular chemical classes, e.g., proteins, lipids, or polysaccharides. It has been found that the tight binding of the agents to these components causes an increase (at least by a factor of 2) in the longitudinal ($1/T_1$) and transverse ($1/T_2$) relaxivity of water protons by the metal complex. Relaxivity enhancement is apparently due in large part to an alteration in the effective correlation time of the electron-nuclear interaction, as described in Lauffer et al. (1985) Magn. Res. Imaging 3, 11.

In the agents of the invention, the toxic paramagnetic ion (e.g., gadolinium) is strongly complexed by a chelating agent to reduce toxicity; it has been found that such agents are effective in reducing T_1 and T_2 (discussed below), despite the relatively lower accessibility of the paramagnetic ion to the surrounding water protons.

Examples of classes of chelating substances of the invention are porphyrins, cryptate compounds, and bis, tris, or tetra-catechol compounds.

The contrast agents of the invention which bind tightly to proteins are also taken up specifically by human hepatocytes, compared to human reticuloendothelial cells, and, because hepatocytes make up the bulk of the liver, provide superior NMR imaging of the liver. The agents thus allow visualization of hepatocarcinoma or metastatic tumors of the liver, whose cells take up the agents at a different rate, or retain the agent for a different length of time, than normally functioning hepatocytes. The invention also allows the use of NMR

imaging to monitor liver function, as manifested by uptake or retention rates of the contrast agents of the invention.

Other features and advantages of the invention will be apparent from the following description of the preferred embodiments thereof, and from the claims.

Description of the Preferred Embodiments

Preferred embodiments of the invention are described below.

Properties of Contrast Agents

Many agents of the invention will have utility in a wide range of applications, because the chemical requirements for tight binding to many components are the same, and also because in some instances the same properties which induce tight binding also influence tissue specificity. For example, the properties of agents which cause selective uptake by hepatocytes compared to reticuloendothelial cells also cause tight binding of the agents to proteins, e.g., intracellular proteins of hepatocytes.

The preferred NMR contrast agents of the invention possess a number of physical/chemical properties, discussed below, related to their utility in diagnostic applications.

In order for agents which are targeted to provide the NMR contrast needed for imaging, they must alter the proton NMR relaxation time in the target component. Thus the agents must have properties which cause them to selectively be taken up by or bound to the target. This is achieved either by means of a higher rate of uptake of the contrast agent by the target, or by a different retention profile between target and non-target tissues. NMR contrast is achieved by the

altering, by the paramagnetic portion of the agent, of T_1 (longitudinal relaxation time) or T_2 (transverse relaxation time) of the water protons in the target.

As mentioned above, one tissue component to which the agents of the invention can bind are proteins. These can be intracellular proteins, e.g., the proteins such as ligandin (also known as Y protein or glutathione-S-transferase (EC 2.5.1.18) and Protein A (also known as Z protein or fatty acid binding protein) inside hepatocytes (J. Clin. Invest. 48, 2156-2167 (1969)). Where the agents are targeted to particular cells such as hepatocytes, it is generally the cells, and not the intracellular proteins themselves, to which the agents are targeted as a result of the properties of the agents, which properties in turn cause tight binding to the intracellular proteins of those cells.

Agents which have protein-binding properties can bind not only to intracellular proteins but also to serum proteins such as human serum albumin (HSA). This binding provides selective enhancement of intravascular structures or patterns on NMR images, permitting diagnosis of blood/brain barrier disruptions caused, e.g., by strokes and brain tumors, and also permitting flow imaging of the blood. For example, some agents can bind to both HSA and ligandin *in vivo*, and thus represent dual intravascular-hepatobiliary agents.

Another important protein which is bound tightly by the protein-binding agents is the immature, poorly cross-linked collagen present in tumors. This collagen can be bound tightly by NMR contrast agents which comprise a paramagnetic metal ion complexed with a

porphyrin. When these proteins are bound, the agent serves the dual roles of tumor targeting and relaxivity enhancement.

Protein binding is provided for by the incorporation of hydrophobic groups into the agent, and providing the agent with the proper net charge.

Hydrophobic Binding

Binding is promoted when both the contrast agent and the protein contain one or more hydrophobic domains; the contrast agent binds non-covalently to the protein through Van der Waals interactions between the hydrophobic domains, thus enhancing binding.

Where the target is a protein, lipophilicity enhances binding of the contrast agents to the protein. Lipophilicity is provided by a non-polar structure, the presence of at least one aryl group (e.g., a substituted or unsubstituted phenyl ring), at least one halogen atom, and/or hydrophobic alkyl groups. For lipophilicity, it is also desirable that the contrast agent not carry excessive charge, i.e., of absolute value greater than 4, at physiological pH.

Lipophilicity is expressed in terms of octanol:water coefficient, determined by introducing a small amount (0.1 mM) of the radiolabeled contrast agent into equal volumes of octanol and Tris buffer (50 mM, pH 7.4). The coefficient of the agents of the invention is preferably at least 0.005, and more preferably at least 0.01.

Another index related to lipophilicity is that of protein-binding. Binding capacity can be expressed as the percentage of the agent bound to 4.5% human serum albumin (HSA) at a concentration of 0.2 mM of the agent, as determined by equilibrium dialysis. For

protein-targeted agents, preferably at least 15%, and more preferably at least 50%, of the agent, binds to HSA.

Electrostatic Interactions

Binding may be further increased if electrostatic interactions between the contrast agent and protein are possible. Thus, if the protein is known to have positively charged binding sites (e.g., human serum albumin) or if the protein is known to have the highest affinity for anionic ligands (e.g., albumin, ligandin or Protein A), then the net charge on the agent should be negative, preferably -1 to -4. Also, direct electrostatic interactions with positively charged residues may be promoted if the agent has additional negatively charged groups (e.g., sulfonate or carboxylate) that are not coordinated to the metal ion in solution.

Alternatively, if the binding sites are known to have anionic character, the agent should have overall positive charge.

Molecular Weight

The agents preferably have a molecular weight of at least 250, and more preferably over 300.

Solubility

To facilitate administration and uptake, the agents should have good water solubility, and preferably should be soluble to a concentration of at least 1.0 mM in normal saline at $20^{o}C$.

Relaxivity

The contrast agents of the invention must, as mentioned above, lower either T_1 or T_2 or both. The ability to achieve this is referred to as "relaxivity."

Relaxivity is optimal where the paramagnetic ion, when bound to the chelating ligand, still has one

or more open coordination sites for water exchange. Generally, one or two such sites are preferred, since the presence of more than two open sites in general will unacceptably increase toxicity by release of the metal ion _in vivo_. However, zero open coordination sites may also be satisfactory, though not preferable, since second coordination sphere water molecules are still relaxed and binding-enhancement is still possible.

In vitro relaxivity is expressed in units of s^{-1} mM^{-1}, or change in $1/T_1$ or $1/T_2$ per mM agent, as measured in saline at 20 MHz. Preferably the agents have an _in vitro_ relaxivity of at least 0.5 s^{-1} mM^{-1}, more preferably at least 1.0 s^{-1} mM^{-1}.

Relaxivity can also be measured _in vivo_ for the tissue component of interest. _In vivo_ relaxivity is expressed in units of s^{-1} (mmol/gram of tissue)$^{-1}$, representing the change in $1/T_1$ or $1/T_2$ above that of saline-injected controls caused by the agents, divided by the concentration of the agent (in mmol/gram of tissue). Tissue concentration is measured using agents made with radiolabeled paramagnetic ions. Preferably, the _in vivo_ relaxivity of the agents in liver tissue is at least 1.0 s^{-1} (mmol/g)$^{-1}$. The agents should bind sufficiently tightly to enhance relaxivity by a factor of at least 2. This increased relaxivity will allow for lower doses of the contrast agents and thus a higher margin of safety in their use.

To maximize the degree of relaxivity enhancement, it is desirable to maximize the rigidity of the binding interaction. Preferably, this is achieved by providing the contrast agent with at least one aryl or aliphatic group which makes multiple contacts with

the biological binding site, preventing free rotation. Additionally, free (non-coordinating) charged groups (e.g., sulfonate or carboxylate) can be incorporated into the agent to promote electrostatic interactions with positively charged amino acid residues; this will increase both the binding affinity and rigidity.

A different strategy to increase the relaxivity of metal complexes is to alter the configuration of the donor atoms around the metal ions to achieve the most symmetrical orientation. This symmetry of the ligand field may lead to longer electron spin relaxation times, and higher relaxivities. The DOTA ligands for Gd^{+3} (described below) are an example in which the symmetry is very high (almost cubic) compared to, e.g., DTPA-derived ligands (described below), which wrap around the metal ion in an anisotropic fashion. An additional benefit of symmetry-constrained macrocyclic ligands like DOTA is their high kinetic stability (vide infra).

Toxicity

The contrast agents must have acceptably low toxicity levels at the dosage required for contrast enhancement, and preferably have an LD_{50} of at least 0.05 mmol/kg. Toxicity of the contrast agents is a function of both the inherent toxicity of the intact complex, and of the degree to which the metal ion dissociates from the chelating agent; toxicity generally increases with the degree of dissociation. For complexes in which kinetic stability is low, a high thermodynamic stability (a formation constant of at least 10^{15} M^{-1}, and more preferably at least 10^{20} M^{-1}) is desirable to minimize dissociation and its attendant toxicity. For complexes in which kinetic

stability is comparitively higher, dissociation can be minimized with a lower formation constant, i.e., 10^{10} M^{-1} or higher. Kinetically stable complexes generally contain a paramagnetic metal ion, e.g., gadolinium (III), complexed with a highly constrictive chelating agent, e.g., dibenzo-1, 4, 7, 10-tetraazacyclotetradecene 1, 4, 7, 10-tetraacetic acid (dibenzo-DOTA).

Toxicity is also a function of the number of open coordination sites in the complex; the fewer open coordination sites, the less tendency there is, generally, for the chelating agent to release the cytotoxic paramagnetic ion. Preferably, therefore, the complex contains two, one, or zero open coordination sites. The presence of one or even two open coordination sites can be acceptable in agents in which the paramagnetic substance has a high magnetic moment (i.e., is strongly paramagnetic), and can thus affect T_1 or T_2 at a low dosage; an example is gadolinium, which is strongly paramagnetic owing to its seven unpaired electrons.

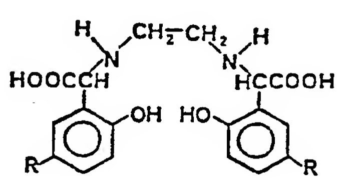
The paramagnetic portion of the contrast agents of the invention can be any paramagnetic ion of the transition metal or lanthanide series which has at least one, and more preferably five or more, unpaired electrons, and a magnetic moment of at least 1.7 Bohr magneton. Suitable ions include gadolinium (III), iron (III), manganese (II and III), chromium (III), copper (II), dysprosium (III), terbium (III), holmium (III), erbium (III), and europium (III); most preferred are gadolinium (III), and iron (III), and manganese (II).

Chelating Ligand

The following discussion applies to chelating ligands which cause the agents of the invention to bind tightly to proteins and to be selectively taken up by functioning hepatocytes.

The organic chelating ligand should be physiologically compatible and preferably contains at least 1 aryl ring which may be substituted with halogen atoms and/or C_1-C_{10} alkyl groups. The molecular size of the chelating ligand should be compatible with the size of the paramagnetic substance. Thus gadolinium (III), which has a crystal ionic radius of 0.938Å, requires a larger chelating ligand than iron (III), which has a crystal ionic radius of 0.64Å. Preferably, the chelating ligand is a single multidentate ligand. Such ligands maximize the stability of the contrast agents towards hydrolysis, and minimize the transfer of the metal ion from the contrast agent to binding sites on the target component.

One suitable class of chelating ligands are ethylenebis-(2-hydroxyphenylglycine) ("EHPG"), and derivatives thereof, including 5-Cl-EHPG; 5-Br-EHPG; 5-Me-EHPG; 5-t-Bu-EHPG; and 5-sec-Bu-EHPG. EHPG and derivatives thereof have the structure:

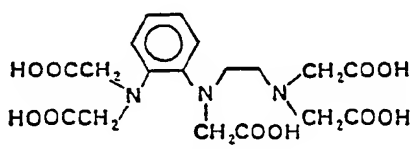


EHPG

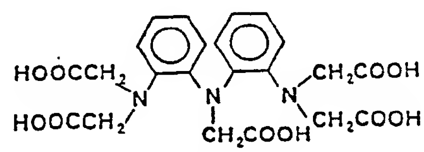
R= Cl, Br, I, CH_3, t-Bu, sec-Bu

Although substitution at the 5 position of EHPG is the most effective in increasing lipophilicity, substitution at any position on the two phenyl rings can be used.

Another suitable class of chelating ligands are benzodiethylenetriamine-pentaacetic acid (benzo-DTPA) and derivatives thereof, including dibenzo-DTPA; phenyl-DTPA; diphenyl-DTPA; benzyl-DTPA; and dibenzyl-DTPA. Two of these compounds have the structures shown below:

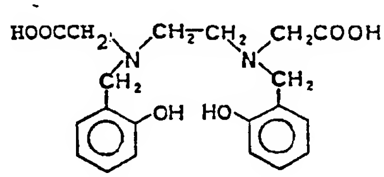


benzo-DTPA



dibenzo-DTPA

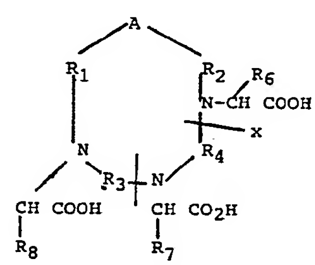
Another class of suitable chelating ligands are bis-2 (hydroxybenzyl)-ethylene-diaminediacetic acid (HBED) and derivatives thereof. The structure of HBED is shown below:

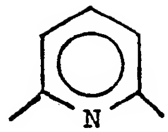


HBED

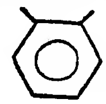
The HBED ligand advantageously has a very high formation constant for iron of 10^{40}. This ligand is available from the Strem Chemical Company.

Another suitable class of chelating ligands is the class of macrocyclic compounds which contain at least 3 carbon atoms, more preferably at least 6, and at least two hetero (O and/or N) atoms. The macrocyclic compounds can consist of one ring, or two or three rings joined together at the hetero ring elements. One suitable class of mono-macrocyclic chelating ligands has the general formula

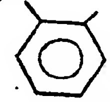


where A is -N- or  , X is 0 or 1, each R_5, R_6,

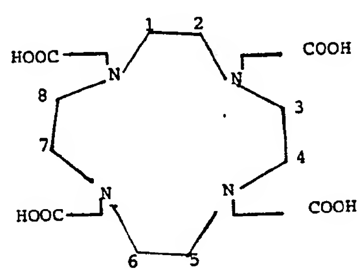
$R_5-CH_2CO_2H$

R_7, and R_8, independently, is H or methyl, and each, R_1, R_2, R_3, and R_4, independently, is ethyl, propyl, butyl, pentyl, or  , provided that when A is -N- ,

$R_5-CH_2CO_2H$

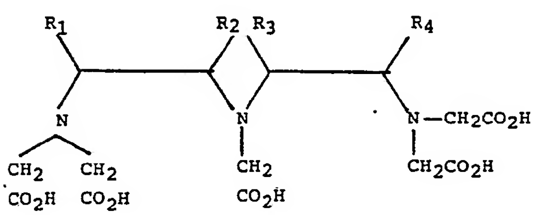
at least one R group must be . The aryl groups may be substituted with halogen atoms or C_1-C_4 alkyl groups. Examples of suitable macrocyclic ligands include benzo-DOTA, where DOTA is 1, 4, 7, 10-tetraazacyclotetradecane-1, 4, 7, 10-tetraacetic acid; dibenzo-DOTA; benzo-NOTA, where NOTA is 1, 4, 7-triazacyclononane- N, N', N''-triacetic acid; benzo-TETA, where TETA is 1, 4, 8, 11-tetraazacyclotetradecane-1, 4, 8, 11-tetraacetic acid; benzo-DOTMA, where DOTMA is 1, 4, 7, 10-tetraazacyclotetradecane-1, 4, 7, 10-tetra(methyl tetraacetic acid); and benzo-TETMA, where TETMA is 1, 4, 8, 11-tetraazacyclotetradecane-1, 4, 8, 11-(methyl tetraacetic acid).

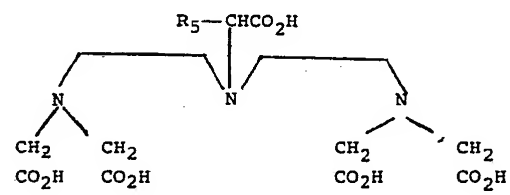
Hydrophobicity, and thus lipophilicity, can also be provided, in the case of ligands (e.g., DOTA derivatives) containing ethylenediamine portions by attaching the above hydrophobic substituents directly to the ethylene carbon atoms. For example, DOTA has the structure:



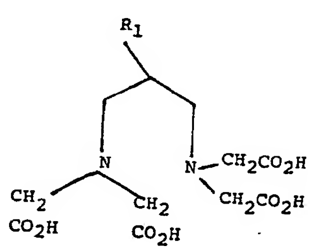
Hydrophobic substituents, e.g., fused phenyl rings or C_{1-5} alkyl groups, can be attached to one or more of carbon atoms 1-8 of DOTA.

Another suitable class of chelating ligands are DTPA derivatives containing hydrophobic substituents. Structures of suitable such derivatives are given below, in which each R_1, R_2, R_3, R_4 and R_5, independently, can be a C_{6-10} aryl group, e.g., phenyl or benzyl; or a C_{1-5} aliphatic group, e.g., methyl or ethyl.

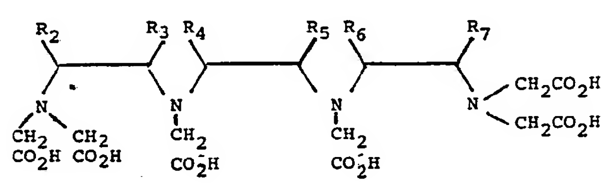




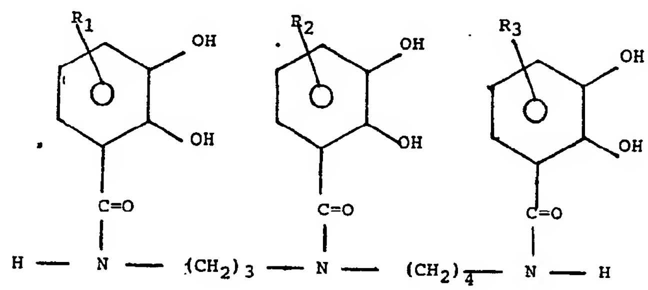
Another suitable class of chelating ligands are derivatives of 1,3-propylenediaminetetraacetic acid (PDTA) and triethylenetetraaminehexaacetic acid (TTHA), given below. Each R_1, R_2, R_3, R_4, R_5, R_6, and R_7 group, independently, can be a C_{6-10} aryl group, e.g., phenyl or benzyl; or a C_{1-5} aliphatic group, e.g., methyl or ethyl.



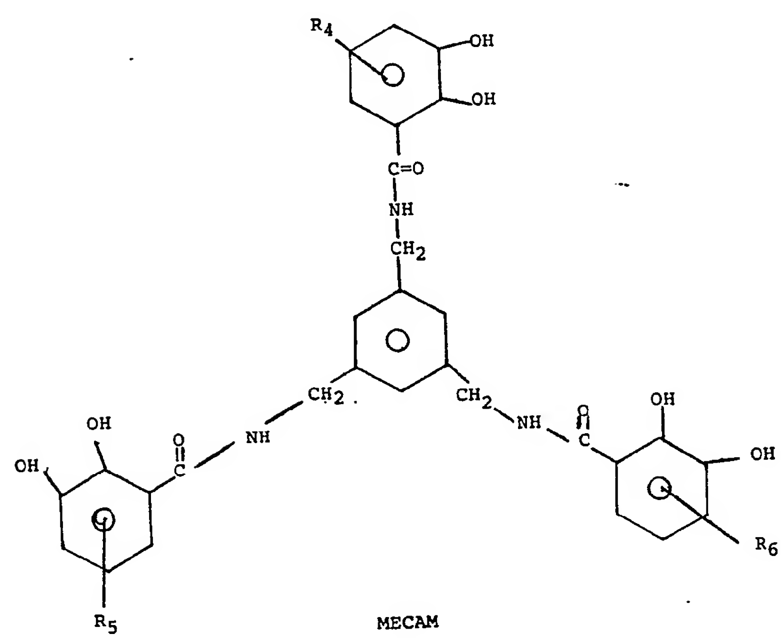
PDTA



Another suitable class of chelating ligands are derivatives of 1,5,10-N,N^{1},N^{11}-tris(2,3-dihydroxybenzoyl)-tricatecholate (LICAM) and 1,3,5-N,N',N''-tris(2,3-dihydroxybenzoyl)aminomethylbenzene (MECAM), having the structures given below. Each R_1, R_2, R_3, R_4, R_5, and R_6, independently, can be CO_2H, SO_3H, H, a halogen, e.g., Cl, or a C_{1-5} alkyl group, e.g., methyl or ethyl.



LICAM



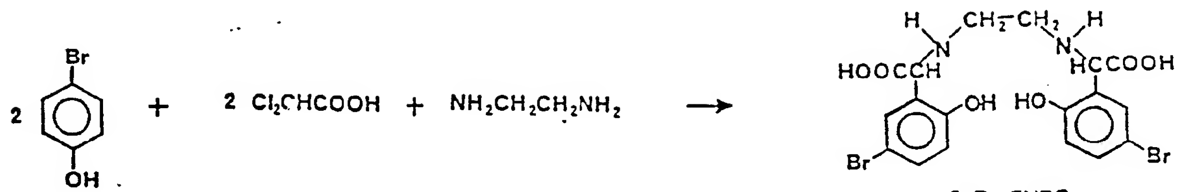
MECAM

<u>Synthesis</u>

The contrast agents of the invention can be synthesized from commercially available or readily synthesized reagents using conventional synthetic methods. In general, a salt of the paramagnetic ion is added to a slightly alkaline (pH 7.4-9) aqueous solution of the chelating ligand and the resulting mixture is stirred for 3-24 hours at room temperature. The resulting contrast agent is then used immediately or stored in lyophilized form or in physiological buffer until use.

The synthesis of iron (III)-$(EHPG)^-$ is carried out as follows. EHPG (Sigma) is dissolved at room temperature in distilled, deionized water maintained at pH 8-9 by addition of 1M NaOH. Solid $FeCl_3.6H_2O$ is added to the solution and the pH adjusted to 7.4 with 1M NaOH. The resulting dark red solution is then stirred at room temperature for 30 minutes, after which it is filtered with 0.2 mm micropore filters (Gelman). The concentration of iron (III)-$(EHPG)^-$ is determined by visible absorption of diluted aliquots using a Beckman Spectrophotometer and an extinction coefficient at 480 nm of 4300 $CM^{-1}M^{-1}$.

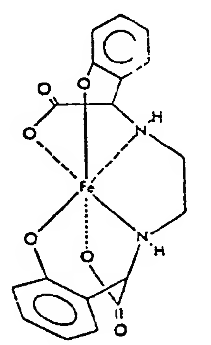
To make iron chelates of EHPG derivatives the first step is to make the appropriate EHPG derivative, according to Mannich reaction, described in Theodorakis et al. (1980) J. Pharm. Sci <u>69</u>, 581; the reaction employs ethylenediamine, dichloroacetic acid, and the appropriate parasubstituted phenol. The reaction scheme for 5-Br-EHPG is:



5-Br-EHPG

Iron (III)-(5-Cl-EHPG)$^{-}$, iron (III)-(5-Bu-EHPG)$^{-}$, iron (III)-(5-Me-EHPG)$^{-}$, and iron (III)-HBED are prepared in analogous fashion to iron-EHPG.

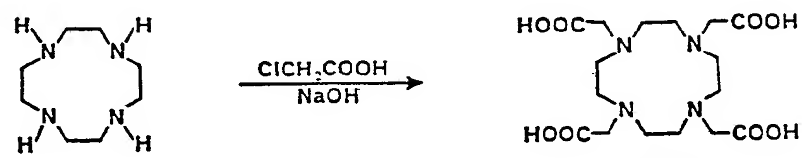
The structure of iron-EHPG is:



The octanol/water partition coefficients and HSA binding percentages of Iron-EHPG, Iron-(5-Br-EHPG), and Iron (HBED) are shown below:

	[octanol] / [water]	% bound to HSA
Iron-EHPG	0.013	17
Iron-(5-Br-EHPG)	0.89	82
Iron-HBED	0.050	34

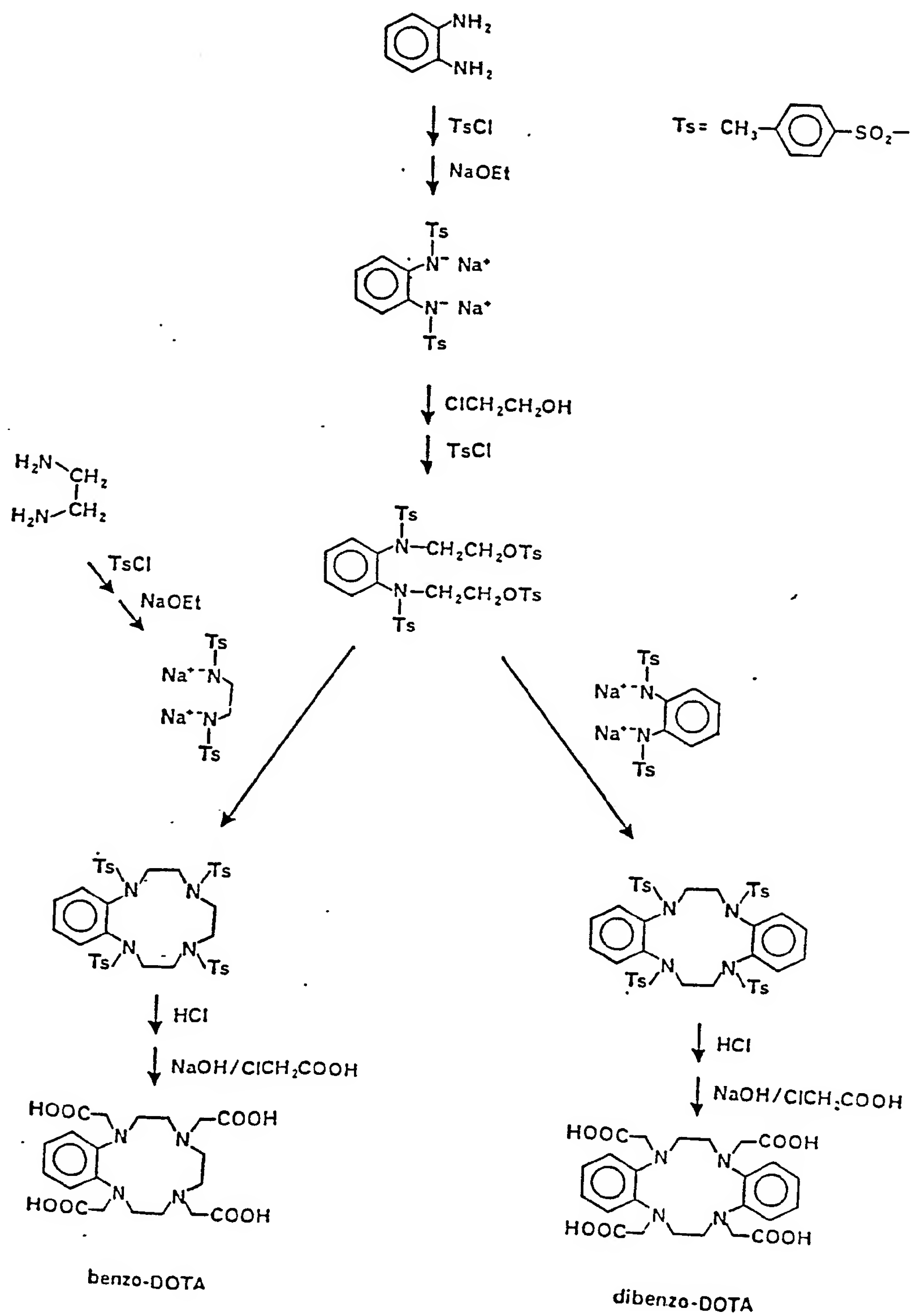
The macrocyclic DOTA chelating ligands are synthesized generally as described in Desreux et al. (1984) Inorg. Chem. 19, 1319, generally according to the reaction



DOTA itself lacks sufficient lipophilic groups for hepatocellular uptake. Two derivatives with the required lipophilicity (provided by fused phenyl rings), benzo-DOTA and dibenzo-DOTA, are made according to the following general reaction scheme. (Alternatively, hydrophobic substituents can be incorporated into, e.g., DOTA, via substituted ethylenediamines prepared according to Meares et al. (Anal. Biochem. 100 152-159 (1979).)

DTPA derivatives (e.g., benzo-DTPA and dibenzo-DTPA) are made by methods analogous to the methods used for making benzo-EDTA (McCandlish et al. (1978) Inorg. Chem. 17, 1383).

Paramagnetic ion chelating ligand complexes made using DOTA derivatives are made generally as described earlier, with a longer time (24 hours) and higher reaction temperatures being required for the formation of metal ion/macrocyclic ligand complexes. A reaction scheme is shown below:


NH2
NH2
TsCl
NaOEt
Ts= CH3-⟨⟩-SO2—
Ts
N⁻ Na⁺
N⁻ Na⁺
Ts
ClCH2CH2OH
TsCl
H2N CH2
H2N CH2
TsCl
NaOEt
Na⁺⁻N
Na⁺⁻N
N-CH2CH2OTs
N-CH2CH2OTs
HCl
NaOH/ClCH2COOH
HOOC
COOH
benzo-DOTA
dibenzo-DOTA

Use

The contrast agents of the invention are administered orally or intravenously in physiological buffer. Dosage depends on the sensitivity of the NMR imaging instrumentation, as well as on the composition of the contrast agent. For example, a contrast agent containing a highly paramagnetic substance, e.g., gadolinium (III), generally requires a lower dosage than a contrast agent containing a paramagnetic substance with a lower magnetic moment, e.g., iron (III). In general, dosage will be in the range of about .001-1 mmol/kg, more preferably about 0.005 - 0.05 mmol/kg.

Following administration of the contrast agent, conventional NMR imaging is carried out; the choice of pulse sequence (inversion recovery, IR; spin echo, SE) and the values of the imaging parameters (echo time, TE; inversion time, TI; repetition time, TR) will be governed by the diagnostic information sought. In general, if one desires to measure T_1, then TE should be less than 30 milliseconds (or the minimum value) to maximize T_1-weighting. Conversely, if one desires to measure T_2, then TE should be greater than 30 milliseconds to minimize competing T_1 effects. TI and TR will remain approximately the same for both T_1- and T_2-weighted images; TI and TR are generally on the order of about 200-600 and 100-1000 milliseconds, respectively.

NMR Imaging Using Iron (III)-(EHPG)

Iron (III)-(EHPG)$^-$ was prepared as described above and used for *in vivo* imaging of rat livers as follows.

Fasted male Sprague-Dawley rats (of average weight of about 400g) were anesthetized with intraperitoneal pentobarbitol (50 mg/kg), placed on a calibrated carrier, and subjected to NMR imaging, along with calibration tubes containing paramagnetically-doped water or agar gels of known T_1 and T_2, to establish an initial baseline image. NMR imaging was performed with a horizontal bore (8cm) superconducting magnet system (Technicare Corp.) at a magnetic field strength of 1.4 tesla (^1H resonance of 61.4 MHz). Images were obtained using a 2-D Fournier transform technique with a slice selection determined by selective irradiation. All images were obtained using 128 phase encoded gradient steps. To maximize T_1 contrast, an IR pulse sequence was used (TE 15 msec, TI 400 msec, TR 1000 msec).

After baseline images were obtained, the rats were removed from the magnet and injected in the tail vein with 0.2 mmol/kg of iron (III)-(EHPG)$^-$. As a comparison, some rats received 0.2 mmol/kg of iron (III)-(DTPA)$^{-2}$ instead. The rats were then reinserted into the magnet, along with the calibration tubes, in the same position as for the initial baseline imaging. Imaging began immediately and continued for 1.5-3 hours. Background-subtracted, region-of-interest intensity values of liver and muscle were obtained for each image; these values were then normalized for any alteration in the signal intensity of the calibration tubes.

The IR 1000/400/15 images of rats which recieved iron (III)-(EHPG)$^-$ demonstrated a marked and prolonged increase in signal intensity of the liver consistent with a short T_1. In contrast, images of

rats which received iron (III)-(DTPA)$^{-2}$ demonstrated only small and transient increases in liver intensity. This is presumably because, unlike iron (III)-(EHPG)$^{-}$, iron (III)-(DTPA)$^{-2}$ distributes throughout the extracellular liver space, rather than in functioning hepatocytes, and is rapidly excreted into the urine.

Ex vivo biodistribution studies measuring the T_1 and T_2 values of excised rat liver, blood, spleen, and thigh muscle at various post-injection times also demonstrated that iron (III)-(EHPG)$^{-}$ is predominantly taken up by functioning hepatocytes, and thus decreases the relaxation times of water protons in these cells.

Rats given intravenous doses of 2.0 mmol/kg of iron-EHPG suffered no apparent ill effects over a two-week observation period.

It is believed that the mechanism of operation of iron-EHPG is as follows. Relaxation time enhancement normally occurs where the unpaired electrons of the paramagnetic substance interact with water molecules directly bound to the paramagnetic substance; the degree of enhancement is inversely related to the distance from the paramagnetic center to the water molecules. In iron (III)-(EHPG)-, however, there are no directly bound water molecules. Relaxation time enhancement, therefore, probably results mainly from the interaction between the paramagnetic substance and indirectly bound, second coordination sphere water molecules. It is believed that since there are a sufficiently large number of these outer-sphere water molecules, appreciable relaxation time enhancement occurs despite the larger distance between the water molecules and the paramagnetic substance.

Other embodiments are within the following claims.

Claims

1. A method of decreasing the NMR relaxation times (T_1 or T_2) of water protons in contact with a biological tissue, said method comprising

administering to a human patient an NMR contrast agent comprising a paramagnetic ion complexed with a chelating substance, said contrast agent being characterized in that it is capable of binding non-covalently and non-immunologically to a component of said tissue, and as a result of such binding is capable of enhancing relaxivity of said water protons by a factor of at least 2, compared to the relaxivity induced by said paramagnetic substance alone free in solution, and

subjecting said patient to NMR imaging.

2. The method of claim 1 wherein said NMR contrast agent has specific affinity for said biological tissue.

3. The method of claim 1 wherein said component is a protein and said contrast agent and said protein each contains one or more hydrophobic domains, so that said contrast agent binds non-covalently to said protein through Van der Waals binding interactions between said hydrophobic domains.

4. The method of claim 1 wherein a domain in said component and said contrast agent are of opposite charge, so that binding is promoted via electrostatic interactions.

5. The method of claim 1 wherein said contrast agent binds to said component via multiple hydrogen bonding interactions.

6. The method of claim 1 wherein said contrast agent binds to said component via more than one of the mechanisms of claims 3-5.

7. The method of claim 3 wherein said biological tissue is blood and said protein is human serum albumin.

8. The method of claim 3 wherein said biological tissue comprises human hepatocytes and said protein is the intracellular protein ligandin or protein A.

9. The method of claim 3 wherein said contrast agent binds to ligandin, Protein A, and HSA and is thus a dual intravascular/hepatobiliary NMR contrast agent.

10. The method of claim 3 wherein said protein is the immature, poorly cross-linked collagen in neoplastic tissue.

11. The method of claim 1 wherein said paramagnetic ion has at least two unpaired electrons.

12. The method of claim 1 wherein said chelating substance contains at least one aryl, aliphatic, non-coordinating sulfonate, or non-coordinating carboxylate group.

13. The method of claim 1 wherein said chelating substance comprises an aminocarboxylate derivative.

14. The method of claim 1 wherein said chelating substance comprises a porphyrin.

15. The method of claim 1 wherein said chelating substance comprises a cryptate compound.

16. The method of claim 1 wherein said chelating substance comprises a bis-, tris-, or tetra-catechol compound.

17. The method of claim 1 wherein said component of said tissue comprises a protein in the liver or bile duct of said patient, said agent being further characterized in that it is taken up preferentially by human hepatocytes, compared to human reticuloendothelial cells.

18. The method of claim 1 wherein said agent is further characterized in that it comprises a complex of said paramagnetic substance and an organic chelating ligand, said complex being characterized in that

it has a solubility to at least 1.0 mM concentration in normal saline,

it has a molecular weight greater than 250, and

it has a charge of an absolute value of 2 or less.

19. The method of claim 1 wherein said agent is further characterized in that it contains at least one aryl ring.

20. The method of claim 17 wherein said complex is further characterized in that its lipophilicity is sufficiently high to cause it to be taken up in greater amount by normally functioning human hepatocytes than by hepatocarcinoma cells.

21. The method of claim 1 wherein the formation constant of said complex is at least $10^{15}M^{-1}$.

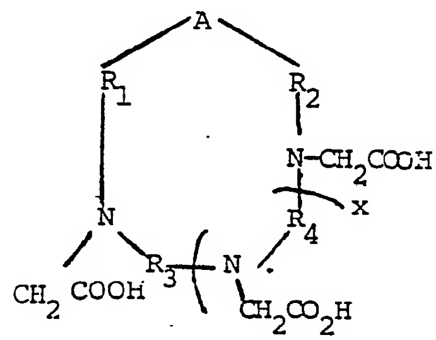
22. The method of claim 17 wherein said agent is further characterized in that it exhibits an octanol:water coefficient of at least 0.005.

23. The method of claim 17 wherein said agent is further characterized in that it exhibits an octanol:water coefficient of at least 0.01.

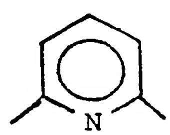
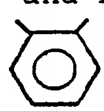
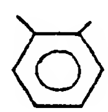
24. The method of claim 1 wherein said agent is further characterized in that at least 15% of said agent binds to 4.5% human serum albumin at a concentration of 0.2 mM agent.

25. The method of claim 24 wherein at least 50% of said agent binds to 4.5% human serum albumin at a concentration of 0.2 mM agent.

26. The method of claim 1 or 17 wherein said macrocyclic compound has the formula



,

where A is $-\underset{\displaystyle CH_2CO_2H}{\overset{|}{N}}-$ or  , X is 0 or 1, and each R_1, R_2, R_3, and R_4, independently, is ethyl, propyl, or  , provided that when A is $-\underset{\displaystyle CH_2CO_2H}{\overset{|}{N}}-$, at least one R group must be  .

INTERNATIONAL SEARCH REPORT

International Application No PCT/US86/01035

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(4): A61B 6/00
US CL.: 128/654

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
US	128/653,654 424/4,9 260/429J

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
Y	US,A, 4,308,249 (FRANK ET AL) 29 DEC. 1981 See the entire document	1-26
Y	US,A, 4,472,509 (GANSOW ET AL) 18 SEPT. 1984 See col. 3, lines 18-66	1,11,17-19, 24-26
A	US,A, 4,150,047 (COE ET AL) 17 APRIL 1979 See the entire document	
A	US,A, 4,352,751 (WIEDER ET AL) 05 OCT. 1982 See the entire document	
A	US,A, 4,331,647 (GOLDENBERG) 25 MAY 1982 See the entire document	
A	US,A, 4,361,544 (GOLDENBERG) 30 NOV. 1982 See the entire document	
X	AU,B, 86 330/82 (GRIES ET AL) 22 JULY 1982 See the entire document	1-6
X Y	EP,B, 0 133 603 (CONIT ET AL) 27 FEB. 1985 , See the entire document	1-6,11-14,19 7-9,15-17,20 21,26

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
25 JUNE 1986	23 JUL 1986
International Searching Authority [1]	**Signature of Authorized Officer** [20]
ISA/US	Jerome R. Smith Jr. Jerome R. Smith, Jr.

Form PCT/ISA/210 (second sheet) (October 1981)

International Application No. PCT/US86/01035

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

X Y	FEBS LETTERS, VOLUME 168, NUMBER 1, ISSUED MARCH 1984. CHEN ET AL. "PARAMAGNETIC METALLOPORPHYRINS AS POTENTIAL CONTRAST AGENTS IN NMR IMAGING pp. 70-74. SEE TH ENTIRE DOCUMENT	1-6,11,12,14 7,8,13,15-17, 26
Y	AJR, MARCH 1984, WEINMANN ET AL, "CHARACTERISTICS OF GADOLINIUM-DTPA COMPLEX: A POTENTIAL NMR CONTRAST AGENT," pp. 619-624 SEE THE ENTIRE DOCUMENT	1-26

V.☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [10]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1.☐ Claim numbers ...., because they relate to subject matter [12] not required to be searched by this Authority, namely:

2.☐ Claim numbers ...., because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [13], specifically:

VI.☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [11]

This International Searching Authority found multiple inventions in this international application as follows:

1.☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2.☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3.☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4.☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.